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Lessons from Western Australia's goldfields water supply scheme

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In July 1896, the parliament of the sparsely populated colony of Western Australia voted to raise a loan of £2·5 million in London to construct a reliable water supply for its booming Coolgardie goldfield, a sum greater than the total cost of the colony's capital works in any previous year. The scheme, prepared by the colony's engineer-in-chief, Charles O'Connor, involved pumping water 565 km along the world's first steel pipeline, which required 77 000 t of steel plate. This paper argues that the scheme was not one of monumental extravagance as its opponents claimed, but was one that was designed using the latest hydraulic research and ultimately was the only one that could have provided the reliability required to sustain the goldfield past its early years. Logistical problems, both in materials supply and in the construction of the pipeline largely through uninhabited country, were huge by contemporary standards. Two important technical innovations, the locking bar pipe and the mechanical pipe caulking machine, helped keep the cost of the project close to budget. The lessons learnt from the long, but eventually successful, battle against corrosion and leakage benefited hydraulic engineers around the world.

1. INTRODUCTION

The Western Australian goldfields water supply scheme was the largest civil engineering project being actively built at the beginning of the twentieth century and at the birth of the Australian nation formed in January 1901 from the five separate Australian colonies. The water supply scheme involved pumping 25·5 Ml/day of fresh water from an impounding reservoir in the hills near Perth on the west coast 565 km eastwards to supply the gold mining centres of Coolgardie and Kalgoorlie and the surrounding goldfields (Palmer, 1904–1905). Unfortunately, the mammoth size of the project and its pioneering engineering were overshadowed by the tragic suicide of Charles O'Connor who, as Western Australia's engineer-in-chief, devised the water supply scheme and managed the major part of its construction. He took his own life in 1902, one year before the scheme was completed after repeated scurrilous personal attacks on him in the press and unfounded attacks on the scheme in the state parliament (PoWA, 1902).

The pipeline was by far the longest water supply pipeline in the world and was the first to be built of steel. It is still the world's longest steel potable water supply pipeline (Figure 1). The 61 856 pipes of 760 mm diameter required for the scheme were fabricated in Western Australia from 77 000 t of imported steel plate. The order for the plate was larger than any order for any previous project – so big that it had to be split between eight different steelworks in three countries. Apart from one shipload of steel plate for pipe jointing rings that was lost at sea in a shipwreck, all the steel arrived in the colony on schedule and without mishap. The 20 steam pumps for the Coolgardie water supply scheme, as the goldfields supply was originally called, were provided by James Simpson & Company of London. The pumps were dispatched in 5000 colour-coded crates, which all arrived in Western Australia without any major losses (James Simpson & Co. Ltd, 1904).

After half a century of near-faultless service, the pumps were replaced by more powerful electric ones in the 1950s. Over the years, the original pipes have undergone many repairs and refurbishments, including reconstruction of the pipeline over nearly 20 years from 1933 as the first major continuously welded above-ground water supply pipeline, the original pipeline having been laid below ground (Fernie and Keating, 1935). The pipeline has served the goldfields and agricultural areas for 105 years without a break in service of more than 2 or 3 days; 58% of the original pipes are still in service, although some have been refurbished twice or even three times (Hartley, 2007). Kalgoorlie's citizens and industries now utilise double the amount of 'scheme' water that O'Connor promised to supply to the mines and people of Coolgardie and Kalgoorlie in 1896. Many people on the goldfields at the time thought that the water would never reach Kalgoorlie but for those who witnessed its arrival it was an event they never forgot and about which they talked for the rest of their lives.

Because the goldfields pipeline was so much longer than any other water supply pipeline in use elsewhere, problems (which, for other water supply utilities seldom became major ones because of the comparatively short lengths of their pipelines and the need to renew pipelines regularly to provide greater capacity) on the goldfields pipeline soon became major concerns. The utility's engineers found themselves faced with problems of corrosion, leakage and water hammer on an unprecedented scale and lessons learnt on the pipeline benefited hydraulic engineers around the world.

The first payable gold to be discovered in Western Australia was found in 1885 in one of the least accessible parts of the

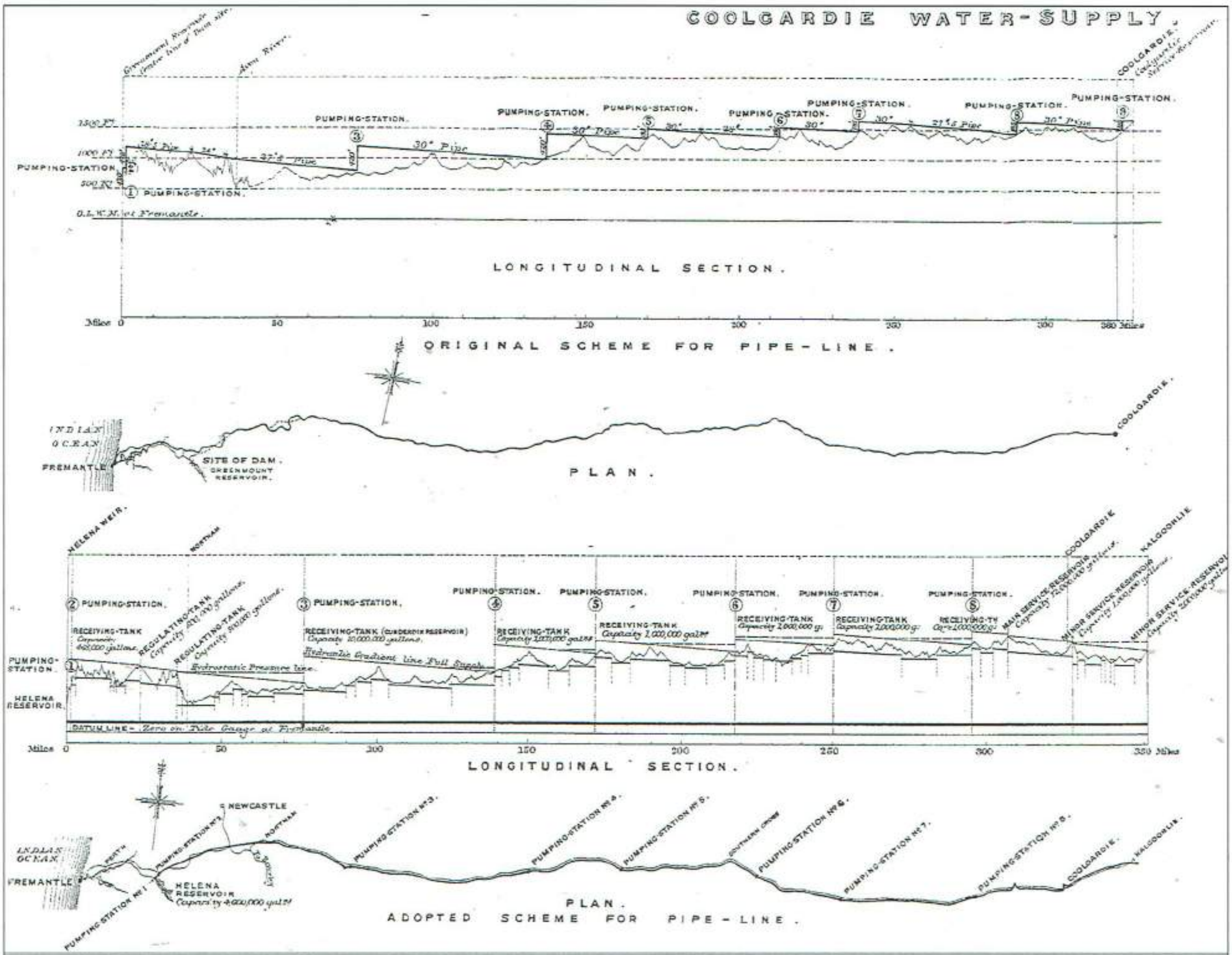

Figure 1. Original drawings of longitudinal section of the commission's scheme and the adopted scheme (Palmer, 1904–05)

colony – the Kimberley region of the far north. After the field's early exhaustion, gold diggers made their way south by sea or over land. Many were experienced prospectors who had 'followed the weight' through the New Zealand and Queensland goldfields. Over the next few years they found a series of goldfields in the colony, including the first in the eastern districts, in 1888, at Southern Cross, 367 km east of Perth. Prospectors were slow to venture further east as no surface supplies of fresh water could be found in the eucalypt woodland, which stretched for another 300 km to the east interrupted only by seasonal saline lakes. Such concerns were put aside in 1892 when a valuable gold find was made at Coolgardie, 180 km east of Southern Cross, which led to the biggest gold rush in Australia since the 1850s. Within 2 months, about a thousand men were camped on the alluvial diggings. In the following year, gold was also discovered at Kalgoorlie, 32 km further east and, by the end of 1895, most of the leases had been pegged on the Kalgoorlie–Boulder Golden Mile, one of the world's richest and most concentrated gold mining centres.

2. WATER FAMINE

Apart from gold, fresh water was the most valuable commodity on the eastern goldfields. Enterprising opportunists sold – at exorbitant prices – 'fresh water' distilled from saline lake water using improvised condensers. To provide sufficient water for the survival of the diggers, government engineers installed numerous small water supply works, including earth dams, catchments on rock outcrops, condensing plants, wells and bores. However, it became increasingly difficult and costly to provide the rapidly expanding population with uncontaminated water supplies by such means and, after 1895, the number of typhoid outbreaks on the goldfields increased alarmingly. At the same time, a speculative boom in 'Westralian' mining shares on the London stock market accelerated the establishment of company mines to exploit underground ore deposits discovered from surface outcrops. The standard stamp battery used to crush mined ore required 9000 l of water for every tonne of ore it crushed. Saline water could be used, but only a few mines could obtain sufficient water of any type to process the ore for more than several months a year. The colonial government was pressed to provide reliable supplies, not only for public health reasons, but also to assist the mining industry. However, the high evaporation rate and lack of suitable dam sites ruled out the development on the goldfields of impounding dams of large enough capacity to store sufficient water to last between the infrequent rains. A source outside the goldfields was thus needed. By mid-1895, O'Connor and his departmental engineers were conducting feasibility studies for a scheme to pump water to the goldfields from a source in the Darling Range, 50 km east of Perth. It was an imaginative concept but, in reality, there were no other practicable means of supplying the mining industry and a population of 40 000 on the eastern goldfields. Even today the only feasible means proposed to supplement supplies to Kalgoorlie is a desalination plant on the south coast and a

pipeline to the city. The colony's premier, John Forrest, also favoured a piped supply from the Darling Range as he realised that it could also be used to provide water for future agricultural development across the thousands of hectares of virgin bushland west of Southern Cross.

When the colony had been granted responsible government in 1890, Forrest had been elected the colony's first premier. He retained the premiership for the whole of the 1890s, arguably the most important decade in Western Australia's history. As a result of responsible government, Western Australia was able to raise money on the London capital market to implement an extensive programme of public works, with the colony's gold finds being accepted as sufficient collateral. In 1891 Forrest had recruited Charles Yelverton O'Connor as the colony's first engineer-in-chief. O'Connor had been trained in Ireland under Institution of Civil Engineers (ICE) indentures and had then spent 25 years in New Zealand, initially building railways and harbours in South Island and later as engineering administrator for the New Zealand government. Forrest's offer came at a time when O'Connor was ready for a move and for new challenges.

During the 1890s, the eastern colonies were suffering their worst depression of the nineteenth century. Many of the unemployed, particularly miners, headed for the Western Australian goldfields. In Perth, O'Connor had no difficulty in staffing the rapidly expanding government railways and public works department with the pick of unemployed engineers and architects from the east. Amongst them was Thomas Hodgson, an experienced hydraulic engineer with a masters degree from Melbourne University who had worked as a consultant to some of the first Victorian irrigation trusts. Soon after he joined the Western Australian public works department, in 1895 Hodgson made an exhaustive investigation into potential dam sites on rivers in the densely forested Darling Range. His subsequent report recommended a site on the Helena River at which Mundaring Weir, the impounding dam for the goldfields water supply, was built. When completed in 1902, the mass concrete gravity dam was the highest in Australia. Because the dam was sited in a narrow gorge it was not provided with a separate spillway. Instead, the dam was designed to pass all floodwaters over the crest of the dam. In 1905 it was claimed to be the highest overflow weir in the world (Figures 2 and 3).

3. WATER AT THE CHEAPEST PRICE

To determine the optimum carrying capacity of a pumped main to serve such a potentially ephemeral entity as a nineteenth century gold mining centre was no easy task. The dam and main could not have been built in less than 3 or 4 years even without the myriad of unavoidable delays inherent in such a project. Some of the world's most famous gold mining centres have been discovered, 'rushed', boomed and then faded back into obscurity in less than 4 years. In the 8 years between O'Connor's first plans for the Coolgardie scheme and its completion, Coolgardie itself went from boomtown to backwater. Fortunately, in the same period, Kalgoorlie grew from a tent encampment to become the regional capital and the state's second town and, in 1903, mines on the Golden Mile between the twin towns of Kalgoorlie and Boulder were among the world's leading gold producers. The Coolgardie scheme was not built to cater for any estimated future demand, but was designed to provide water to the Coolgardie district for sale at a cheap enough price and in sufficient quantities to pay for the construction and operation of the scheme and for its eventual replacement. The government never had any intention of providing a subsidised water supply to the goldfields. The Coolgardie scheme was always intended to be fully self-financing.

In September 1895, engineers in O'Connor's office began working on estimates of the capital cost and annual cost of the scheme for three different delivery rates – 4·5 Ml/day, 22·5 Ml/day and 45·5 Ml/day – and for pipes with diameters from 300 to 1500 mm in both cast iron and wrought iron (PWD, 1895). Both O'Connor and Hodgson were well read in the latest British and American technical journals. Hodgson had examined a number of contemporary versions of the eighteenth century Chezy pipe flow formula before adopting the variant proposed by Swiss engineers Ganguillet and Kutter in 1870, usually known as the Kutter formula. With a pipeline as long as the one needed for Coolgardie, even very small variations in the pipe roughness factor could have had major cost implications. A fairly conservative interpretation of the roughness factor was thus used.

In such an undeveloped colony as Western Australia there were few engineering works that could be used to provide cost precedents, so information on items such as steam pumping costs and the manning of pumping stations was obtained from a wide range of sources in Australia, New Zealand and Britain. The fuel chosen for the pumping stations was coal from the only known coalfield in the colony, at Collie, although the field was still largely undeveloped. This was a surprising choice because local timber was the main fuel used on the goldfields (in the 1900s, over 400 000 t of firewood was used every year in one of the largest industrial uses of timber for fuel anywhere in the world). It is possible that Forrest had urged O'Connor to provide for the potential use of coal in order to stimulate the development of the coal mining industry.

4. STEEL PIPES

Since the 1870s, when the Siemens basic open-hearth steelmaking process first made it possible to mass produce high-quality steel cheaply, steel had begun to replace wrought iron for many structural uses. Hodgson located references in technical journals to the use of steel for water mains in special instances in Europe and the USA, though only for relatively short lengths. Prices were obtained from Melbourne pipe manufacturer Mephan Ferguson for the supply of steel pipes with riveted spiral joints, as Ferguson already held patents for this type of pipe in wrought iron (Ferguson, 1992). Eventually, prices were calculated for steel pipes in sizes and pressure grades equivalent to the iron pipes. These looked promising and the whole set of estimates was recalculated. The cheapest water delivered in iron pipes was pumped at a rate of 22·5 Ml/day in 760 mm pipes and cost 12·5 pence/kl. For steel pipes, this was reduced to 9–25 pence/kl for the same size pipe and delivery rate. Likewise, the capital cost of the project was substantially reduced from £3·56 million for iron pipes to £2·5 million for steel pipes. The scheme was therefore developed on the assumptions that eight pumping stations and 760 mm spiral riveted pipes of 5 mm thick steel were to be used, except for 121 km where, because pressure heads were higher, pipe thicknesses were to be 6 or 8 mm.

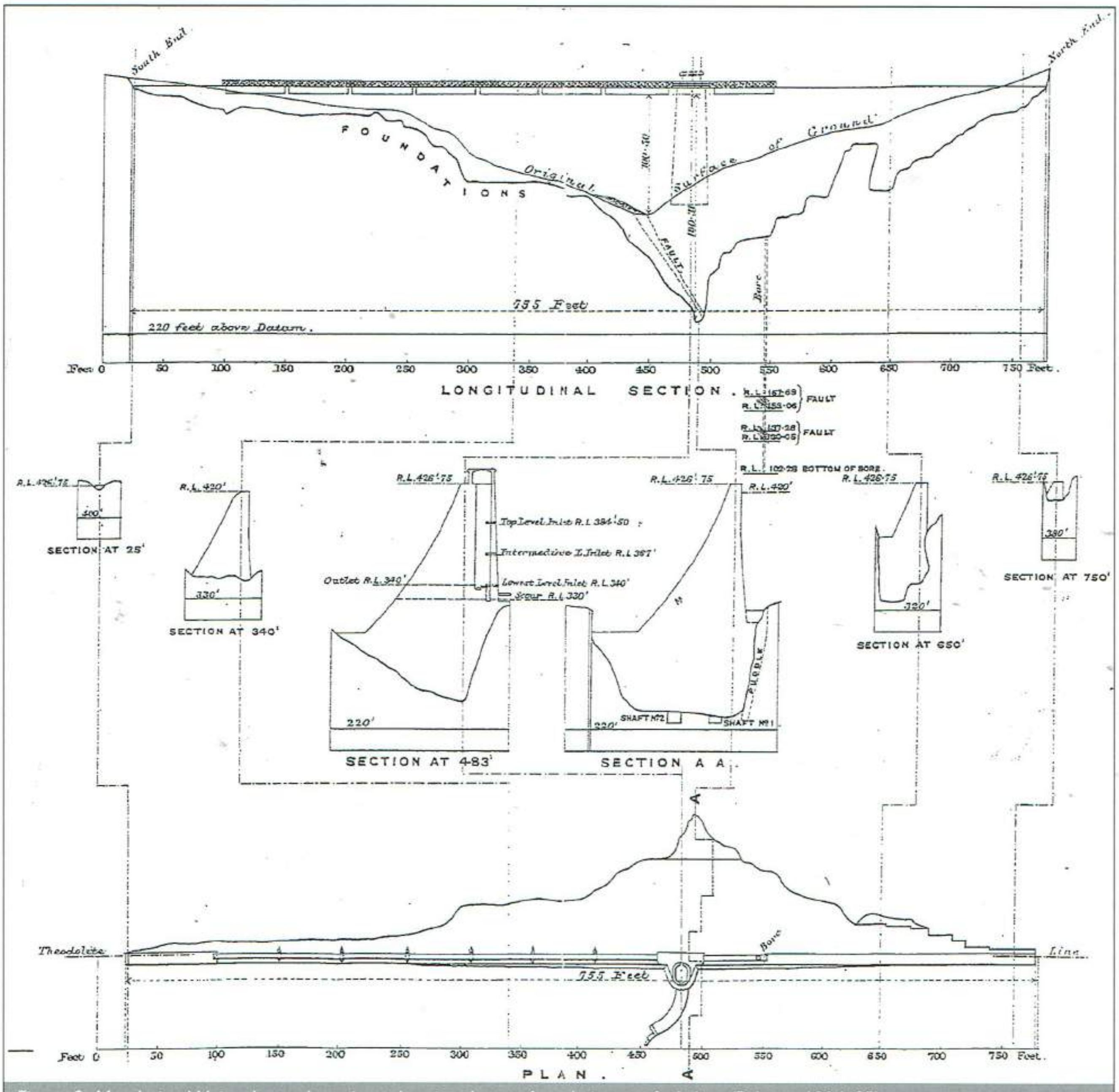

Figure 2. Mundaring Weir: plan and sections showing deeper foundations at fault line (Palmer, 1904–05)

In July 1896, O'Connor tabled in parliament a report setting out clearly how these estimates had been arrived at (O'Connor, 1896). In the report he also recommended that the government arrange for 'a commission of high-class specialists in England' to advise on the pumping stations and pumps for the scheme. This was a shrewd move in the light of the incredulity and scorn expressed at the scheme in parliament and in the press. The recommendation was taken up by the government and O'Connor asked John Carruthers, who had previously been engineer-in-chief in New Zealand but was then the Western Australian government's consulting engineer in London, to invite suitable engineers to join the commission. The three-man commission, which was given a very broad brief, consisted of Carruthers, Professor William Unwin (the foremost British academic hydraulic engineer) and George Deacon (an engineering consultant renowned for his part in the construction of Liverpool corporation's water supply which had its impounding reservoir, Lake Vyrnwy, in North Wales). O'Connor left for London in January 1897 to confer with the commission, taking with him the latest plans of the scheme. He spent 5 months in Britain and on the Continent, mostly on work related to the Coolgardie scheme, including visits to steelworks, pump manufacturers and other engineering works.

O'Connor returned to Perth with the commission's interim report (CoE, 1898), which, most importantly for O'Connor, thoroughly endorsed the practicality of the Coolgardie scheme including the use of steel pipes. For the main part of the pipeline, it recommended 5 mm thick riveted pipes and for high-pressure sections 6 mm gas-welded pipes. The proposal to use gas welding was an interesting one as, in 1897, the technology was still in the experimental stage. Le Chatelier had only discovered the oxy-acetylene flame in 1895 and commercial production of oxygen had only just begun (Savage, 1974).

The main concern of the commission was the large amount of leakage that would be likely from such a long pipeline,

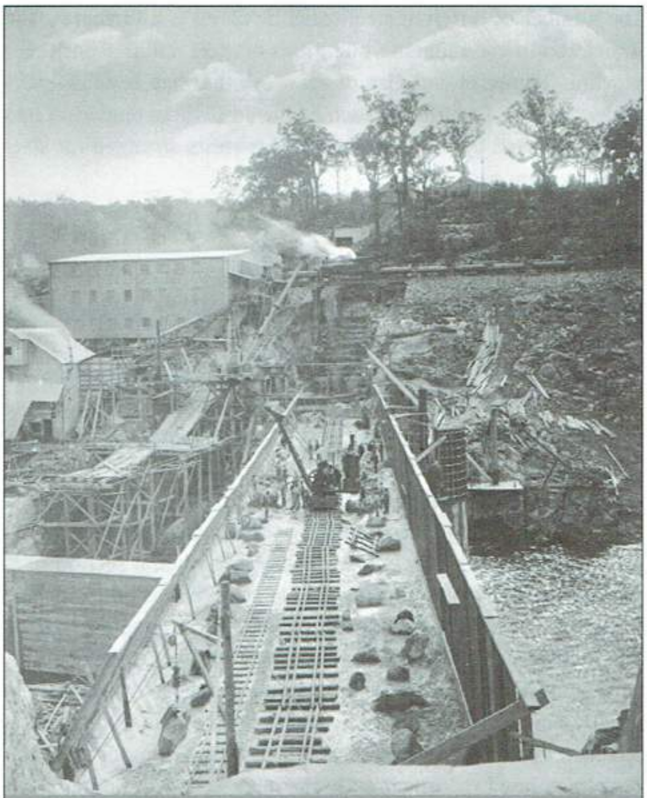

Figure 3. Mundaring Weir under construction

particularly from the riveted sections. To reduce this, the commissioners adopted some novel ideas. They proposed that both types of pipe should be made from a series of single plates so that the pipe had only one longitudinal joint. They enquired about the largest size plates that were rollable: for 5 mm plate, the largest possible pipe diameter was 790 mm and for 6 mm the largest was 740 mm; these were thus the diameters recommended. The steel for the riveted pipes was to be shipped as flat plate and the pipes made in Perth, but the welded pipes were to be factory made. As there would be over 16 000 welded pipes, in order to reduce shipping costs it was recommended that the welded pipes be made in three sizes – 740, 700 and 660 mm – so that they could be shipped nested into each other. Some leakage would be inevitable, so the commission proposed that the whole pipeline be built above ground on timber bolsters so that leakages could be located and mended before they developed into major bursts. To accommodate axial movement caused by daily and seasonal temperature changes, an expansion joint capable of accommodating a movement of 16 mm at 36 m centres was proposed.

The commission also examined other possible pipe types and was impressed by the locking bar pipe invented by Melbourne contractor Mephan Ferguson. The pipe was made from two steel plates. The longitudinal edges of the plates were 'dovetailed', or swollen, as shown in Figure 4. The plates were shaped into semicircles and then both pairs of dovetailed edges were fitted into the grooves in the longitudinal locking bars. These bars were closed by hydraulic pressure exerted over the swollen edges of the plates. However, the commission could not recommend use of the pipe as it had not been manufactured commercially or tested in working conditions.

4.1. Pipe fabrication

Although Hodgson had strong reservations about the commission's recommendation for use of small-diameter welded pipes and its provision for thermal movement, when tenders for the fabrication and supply of pipes were called, the pipe types, sizes and numbers were as recommended by the commission, although no provision was made for expansion joints which had been recommended. Two separate tenders were called, one for the riveted pipes and one for the welded. The international tenders closed in May 1898. Australian contractors submitted the lowest tenders for both types. G. & H. Hoskins of Sydney submitted the lowest one for the riveted pipes. For the welded pipes, O'Connor had allowed contractors to offer alternative types of pipe as long as they were equivalent in performance. Mephan Ferguson offered the locking bar pipe as an alternative and his tender was the lowest in the welded or equivalent category. The total of the two lowest tenders came well within O'Connor's 1896 estimate.

O'Connor sailed to Adelaide where Ferguson had a demonstration locking bar pipe contract and carried out a series of tests on the pipes, which proved satisfactory. He then decided to use 760 mm diameter locking bar pipes fabricated from 6 mm steel for the whole project, except in the high-pressure areas where 8 mm steel was to be used. He negotiated reduced prices with the two lowest tenderers to allow for the single size of pipe and divided

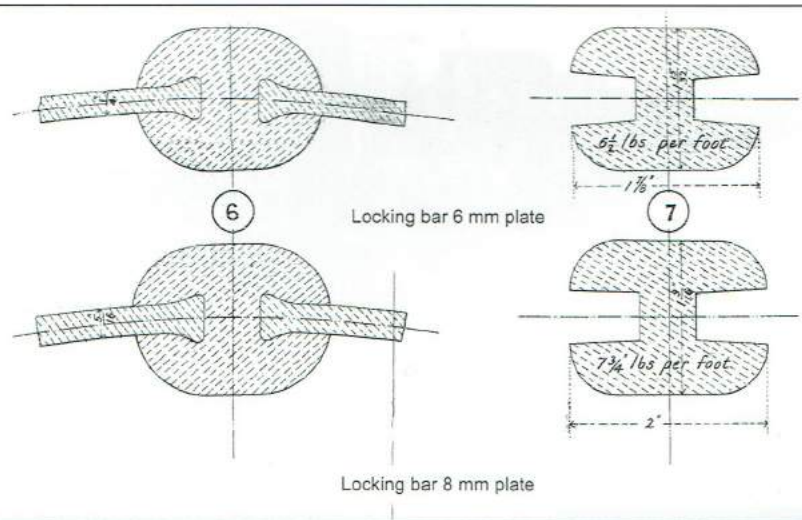

Figure 4. Open and closed locking bars for Ferguson's pipes

the fabrication contract into two equal parts, one for each company. Each contract was still larger than any previous Australian public works contract. As the longitudinal joints on the locking bar pipe seldom leaked even under high pressures, O'Connor decided to lay the pipeline underground so that thermal movements would be minimised. He also agreed with Carruthers on a pipeline friction allowance; this satisfied both Unwin and Hodgson and permitted the pumping head at each of the first four pumping stations to be twice the head at each of the second four stations (Figure 5). This then allowed the pumps to be standardised, with three pumps in the lower stations and two in the upper ones. It was an elegant solution that was the work of a great engineer at the height of his powers.

By the end of 1898, Carruthers and E. H. Wittenoom (the Agent General for Western Australia in London) had formalised contracts with eight separate steel manufacturers to supply the steel for the pipes, locking bars and joint rings (Wittenoom, 1899). For the Hoskins contract:

(*a*) Carnegie Steel Co. (Pittsburgh, USA) supplied all the steel plate for the pipes.
(*b*) Nettlefolds (Newport, South Wales) supplied the locking bars.
(*c*) Ebbw Vale Steel, Iron and Coal Co. (Ebbw Vale, South Wales) supplied the plate for the jointing rings.

Four German steelworks shared the manufacture of the plate for the Ferguson contract:

(*a*) Thyssen & Cie (10 200 t);
(*b*) Actien Gesellschaft der Dellinger (9100 t);
(*c*) Phoenix Actien Gesellschaft der Bergban (7100 t); and
(*d*) Gewerkschaft Grille Funke & Co. (6100 t).

The locking bars and joint ring plate for the Ferguson contract were supplied by Earl Dudley's Ironworks at Tipton (Birmingham, England).

The number of different steelworks involved is a further indication of the immense quantities of steel required for the pipeline (Figure 6) and also of the work that had been undertaken by Carruthers. Each of the steelworks tendering had to be inspected by him and independent tests arranged for steel samples from each steelworks.

4.2. Mechanical caulking

Another innovation, Couston's mechanical joint caulker, played an important role in the successful laying of the goldfields pipeline (Figure 7). The Achilles heel of the locking bar pipe was the leaded joint between pipes. To fill the gap between the steel jointing ring and the pipe, molten lead was poured into a temporary mould around the sleeved joint. When the lead had set, it was manually caulked to make the joint solid. This was done after the pipes had been laid in the trench, so the caulkers found it difficult to consolidate the lead under the pipe. Unsatisfactory joints were only discovered when a section of pipe was tested hydraulically. At that stage it was an expensive exercise to open up the trench at the faulty joint and remake the whole joint. James Couston, a plumbing and water supply contractor, devised, with Hodgson's encouragement, an electrically powered mechanical caulking device. The caulker was attached to a trolley frame so that it could be run along the top of the pipeline from one joint to the next. Lead was poured from another trolley ahead of the caulker. On the caulker, two semicircular frames were fitted over the joint and mechanical rammers on these frames caulked the two halves. With about two-thirds of the pipe joints still to be caulked, the seven machines in use rapidly paid for themselves many times over and the reliability of the joints improved immeasurably.

5. COMPLETION

The goldfields water supply was opened by Sir John Forrest in January 1903, by which time O'Connor had committed suicide and Hodgson had been forced to resign from the public service. Hodgson's assistant, W. C. Reynoldson, completed the construction work and became the goldfields water supply's first chief engineer. In 1904, the official capital cost of the scheme

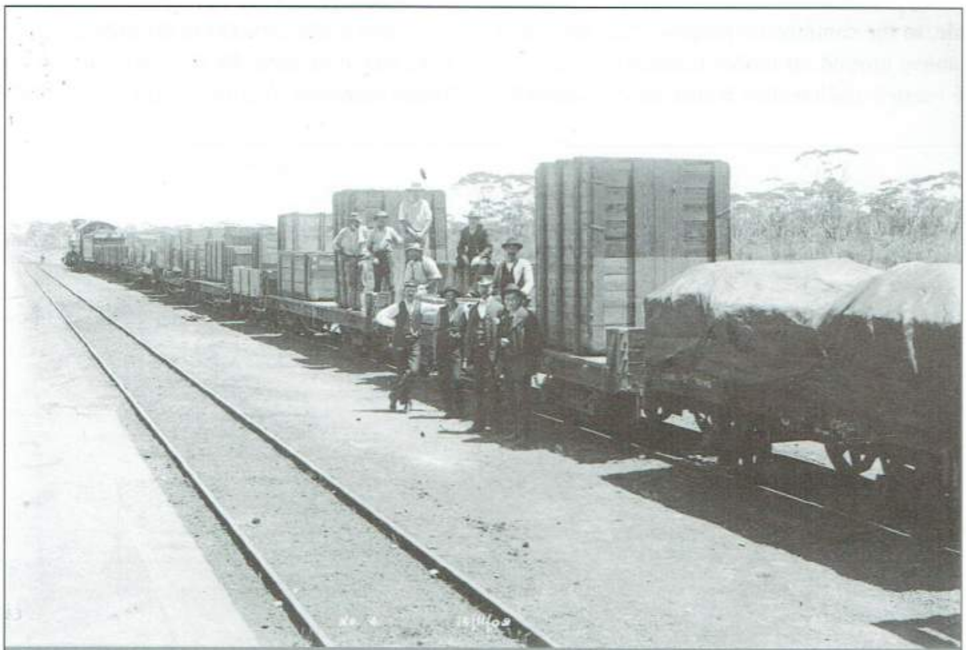

Figure 5. Pumping equipment being delivered by train to No. 4 pumping station at Merredin

Figure 6. Pipes en route for unloading along pipe track

was reported to be £2·66 million. The closeness of this figure with O'Connor's 1896 estimate of £2·5 million is remarkable to say the least. The use of locking bar pipes in a single size and the speed with which the seven pipe-laying crews completed the pipeline after they had been equipped with the mechanical caulkers certainly helped to keep the cost of the completed works so close to the original estimate.

Reynoldson established the operating and maintenance procedures of the pumping station and changed the boiler fuel from coal to the cheaper eucalypt firewood (Figure 8). Pumping station operatives, pipeline bicycle maintenance patrolmen and pipeline repair gangs were the backbone of the service for the next 60 years. Within 4 years of the start of the supply, pipe leaks and bursts caused by internal and external pipe corrosion became a growing problem. External corrosion was the easier to correct through better drainage and suspension of the pipeline, where necessary, in an open trench. Pipe inspections revealed extensive chemical growth along the pipeline in the form of tubercules, which had reduced the carrying capacity of the pipe by between 10 and 50%. On Reynoldson's recommendation, the government engaged a group of specialist consultants, Sir Alexander Binnie, Son & Deacon, Sir William Ramsay and Mr Otto Hehner to advise on remedial measures. Their report (Goldfields Water Supply Administration, 1910) confirmed that the internal corrosion was principally due to dissolved oxygen in the scheme water and suggested two possible remedies. The water leaving the reservoir could be deaerated by spraying it into a vacuum or the water could be dosed with lime to lower its acidity. A trial lime dosage was carried out on a main leaving Kalgoorlie with apparent success and, as it was the cheaper option, lime dosage was implemented, first at No. 2 pumping station and then at No. 1. At the same time, existing structures were altered to prevent aeration occurring during pumping operations and three large summit tanks were built where previously the main had emptied when pumping had ceased. These tanks also increased the length of gravity flow in the main, resulting in more economical pumping. Lime dosage continued for several years but was completely ineffective on corrosion. Moreover, it caused deposition of carbonate in the downstream pipes so severe that the pipes had to be progressively removed, cleaned and replaced. In 1915, work was started on the development of a vacuum deaeration plant capable of treating 27 Ml/day along the principles suggested in a consultants' report (Weller, 1927). Its successful operation and further structural changes made along the main finally put an end to most of the aeration corrosion problems. However, leakage and bursts at the leaded joints between pipes remained a problem until the main was relaid above ground as a continuously welded main in the 20 years from 1933 (Figure 9).

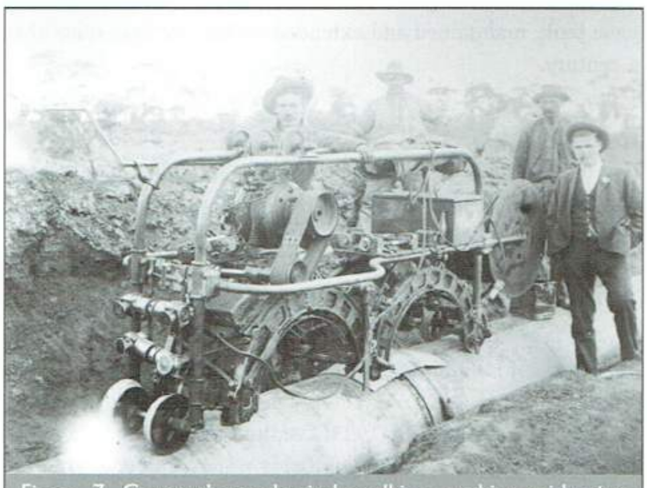

Figure 7. Couston's mechanical caulking machine with pipe perimeter frame lifted and stowed for movement along the top of the pipe

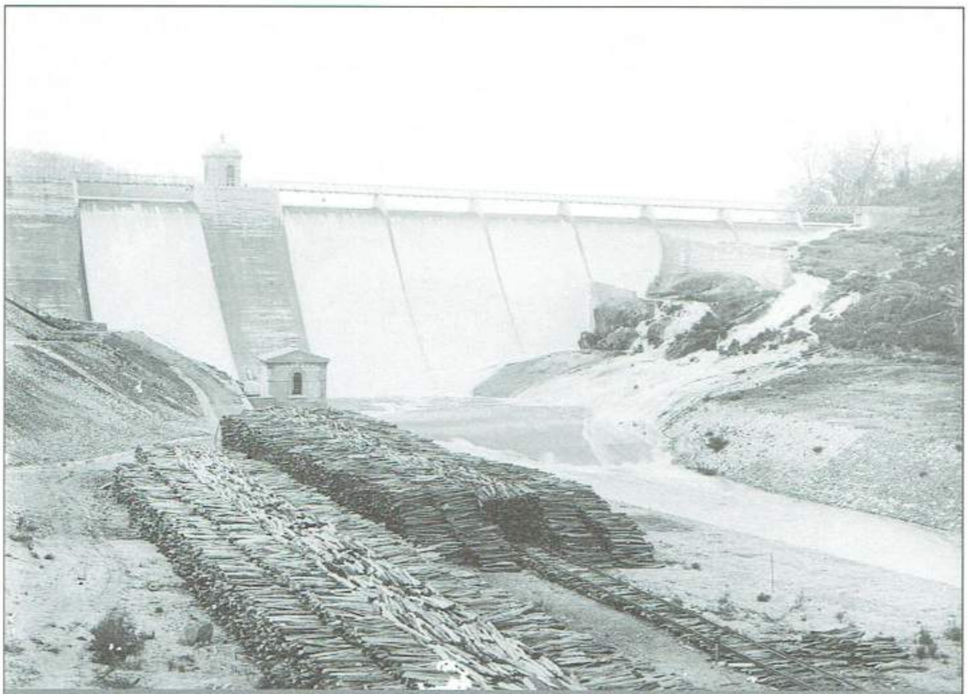

Figure 8. Firewood fuel stacked for No. 1 pumping station at Mundaring

In 1917, Reynoldson's successor as chief engineer, Percy O'Brien, and the senior district engineer, John Parr, submitted a paper to the ICE, which was read in their absence (O'Brien and Parr, 1917–1918). The paper presented the story of the first 14 years of the goldfields supply and the battle against corrosion as a detailed case history that told of the mistakes made as well as the successes. The paper generated extensive discussion and written comments. Aeration corrosion was clearly a problem encountered by many water instrumentalities around the globe. O'Brien and Parr were each awarded the Stephenson Medal and the Telford Premium for their paper; this is believed to be the first occasion these awards were given to Australian residents.

6. CONCLUSION

The two main objectives of the Coolgardie scheme, the provision of an adequate and affordable public water supply for the goldfields communities and a reliable supply to the mining industry, were both achieved within 18 months of the pipeline's completion. Because of the certainty of water supplies, from 1905 the Kalgoorlie mines were able to expand their production of lower grade ore; this extended their operations through the 1920s to Kalgoorlie's second gold boom in the 1930s. The unexpectedly severe aeration corrosion to the pipeline was overcome by 1925, but water losses at the leaded joints became progressively worse and were only held at bay by increasing amounts of repair work. However, the start, in 1933, of the huge task of digging up 565 km of pipeline and reconstructing it above ground as a fully welded conduit heralded the beginning of the end for the leaded joints, even though it took nearly 20 years to remove almost all of them. O'Connor's decision to lay the pipeline underground may be questioned. However, as no proven economical means were available in the 1890s for accommodating or restraining the very large daily and seasonal thermal movements of the pipeline, his decision must surely have been the correct one. The people of Western Australia have good reason to be thankful for his vision. The water supply to the goldfields has been maintained since 1903 without any break in service for longer than 3 days. Today it is still one of the state's most important service arteries and remains a fitting memorial to its designers and to the hundreds of people who have built, maintained and extended the service over more than a century.

Figure 9. Refurbished pipes distributed by camel jinker in 1927 along a section of pipeline not accessible by rail, 160 km from Kalgoorlie

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